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Abstract

The parameters of the ITER core plasmas will be measured using the Core Imaging X-ray Spectrometer (CIXS), a high-resolution crystal spectrometer focusing on the L-shell spectra of highly ionized tungsten atoms. In order to correctly infer the plasma properties accurate atomic data are required. Here, some aspects of the underlying physics are discussed using experimental data and theoretical predictions from modeling.

Introduction

The ion-temperature, T_i, and poloidal and toroidal rotation velocity profiles, v_ϕ and v_θ, of the ITER core plasmas will be measured using the Core Imaging X-ray Spectrometer (CIXS) [1]. The instrument is being designed for Doppler measurements of the L-shell spectra of highly charged tungsten ions. Centered on the spectrum of Ne-like W LXV, the $n = 2 - 3$ transitions fall in the 8 – 12 keV (1.0 – 1.5 Å) x-ray interval [2], where the high-resolution crystal spectrometer will focus on one or a few spectral lines for measurements of line profiles and shifts. The CIXS may also include a broadband moderate-resolution x-ray calorimeter to facilitate diagnostics of the ITER core electron temperatures, T_e, and ion impurities [3]. To interpret the spectra and take full advantage of the diagnostic capabilities of the CIXS, accurate radiative and collisional data for W L- and M-shell ions are required together with K-shell data on mid-Z elements whose radiation may also show up in the spectral region of interest. Several spectroscopic studies on highly charged tungsten ions applicable to CIXS have been carried out using electron beam ion trap (EBIT) spectroscopy [2, **?**, 4, 5, 6, 7]. At the Livermore EBIT facility, the WOLFRAM project aims to provide accurate experimental and theoretical data on tungsten ions of relevance to magnetic fusion diagnostics [6]. Figure 1 shows a spectrum of W L-shell transitions measured at the Livermore SuperEBIT electron beam ion trap using an x-ray calorimeter spectrometer [5].

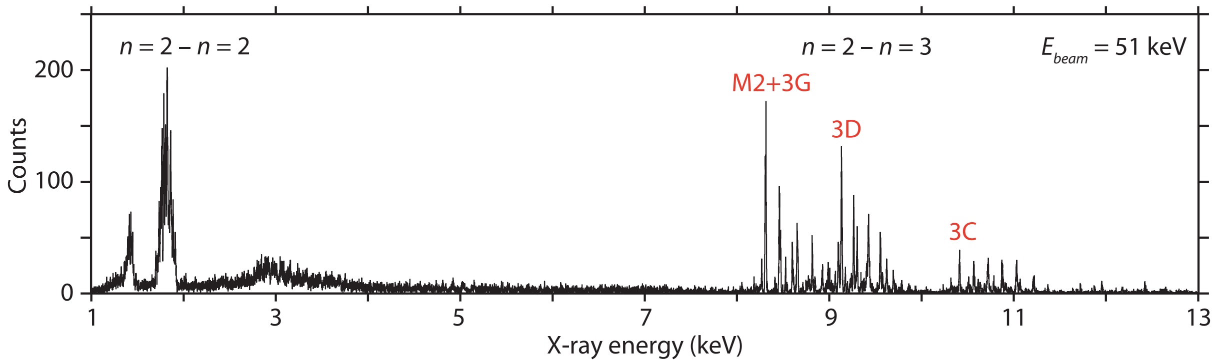

Figure 1: Experimental tungsten spectrum measured at the Livermore SuperEBIT at an excitation energy of E_{beam} = 51 keV using an x-ray calorimeter with a resolution of ~7 eV. Labeled lines are from Ne-like W LXV.

Advantages of tungsten as ITER core diagnostic radiation

Tungsten (Z = 74) was chosen as the medium to probe the parameters of the ITER core plasmas since it will exist as an indigenous impurity in ITER plasmas and provide strong x-ray emission over a large electron temperature range. This is especially true for Ne-like W^{64+}, which – due to its closed-shell structure – has a fractional abundance of more than 10 % between 12 and 33 keV, see Fig. 2. Mid-Z elements predicted to be found in ITER plasmas, such as Ar (Z = 18), Fe (Z = 26), and Cu (Z = 29), will mostly be fully stripped in the core plasmas, with expected electron temperatures between 20 and 40 keV. An earlier design of the CIXS instrument was therefore open to the possibility of introducing Kr (Z = 36) into the tokamak for the study of the He-like Kr XXXV spectrum [8]. To compare the strengths of the Kα emissions from He-like Kr XXXV to the L-shell transitions in Ne-like W LXV, the spectra have been calculated using the Flexible Atomic Code, FAC v.1.1.1 [9] and modeled for steady-state ITER plasma conditions, see Table 1.

It is clear that the diagnostically interesting tungsten lines are much brighter than the krypton lines. However, it is important to note that the total ionization energy of almost 140 keV required to create a Ne-like W^{64+} ion [11] is about 3.5 times higher than the roughly 40 keV needed to

Spectrum	Transition	Label	ΔE_{exp}	ε (10 keV)	ε (20 keV)	ε (30 keV)	ε (40 keV)
Kr XXXV	$1s_{1/2} - 2p_{3/2}$	Kα w	13114.68(36)^a	48	84	102	112
Kr XXXV	$1s_{1/2} - 2p_{1/2}$	Kα y	13026.29(36)^a	18	27	31	33
Kr XXXV	$1s_{1/2} - 2s_{1/2}$	Kα z	12979.63(41)^a	11	11	10	8
W LXV	$2p_{1/2} - 3d_{3/2}$	3C	10408.69(40)^b	146	217	244	257
W LXV	$2p_{3/2} - 3d_{5/2}$	3D	9126.25(50)^b	497	696	766	798
W LXV	$2p_{3/2} - 3s_{1/2}$	3G	8307.51(40)^b	288	365	367	356
W LXV	$2p_{3/2} - 3s_{1/2}$	M2	8299.22(40)^b	106	132	115	96

Table 1: Predicted emissivities for transitions in He-like Kr XXXV and Ne-like W LXV for plasmas with $N_e = 10^{14}$ cm^{-3} and T_e = 10, 20, 30, and 40 keV. Emissivities ε are listed in units of photon per ion per second (γ/Z^{q+}/s). Experimental transition energies ΔE_{exp}, in units of electronvolt (eV), are from measurements at the Livermore EBIT facility by [a]Widmann *et al.* [10] and [b]Beiersdorfer *et al.* [7].

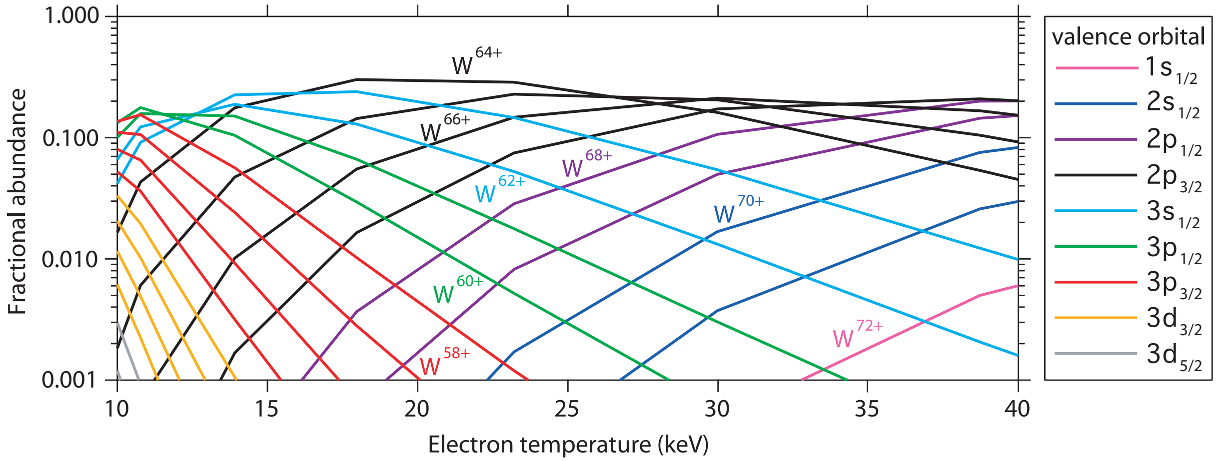

Figure 2: Tungsten charge state distribution for $N_e = 10^{14}$ cm^{-3}.

make a He-like Kr^{34+} ion. Whereas tungsten is expected to be an intrinsic impurity in ITER plasmas, krypton would need to be injected. Even if tungsten would not exist in quantities sufficient to provide enough spectral signal, less tungsten will need to be introduced than krypton due to the much higher line emissivities. For a given signal strength, the energy consumed by W and Kr contribute about the same to the tokamak power balance (excluding bremsstrahlung). This, of course, also strongly depends on the charge state distributions of tungsten and krypton ions and on the transport of the ions from the edge to the core plasmas[1].

Due to the high atomic mass of W, the Doppler widths of the x rays are narrower for W than for Kr and mid-Z ions. This is an important aspect as the spectral range of the CIXS may be limited, e.g. by the use of a double-crystal scheme, presently under consideration to cope with the high ITER neutron fluxes. Additionally, it is easier to find crystals with appropriate 2d spacings and high reflectivities for W than for Kr x rays.

Atomic data needs

Accurate atomic data on highly charged tungsten ions are critical for the success of the ITER CIXS instrument. In order to infer the ion temperatures, T_i, and bulk rotational velocities, v_ϕ and v_θ, of the ITER plasmas from the Doppler effect the rest line positions and shapes (strengths and widths) of the W L-shell x-ray transitions must be well known from laboratory measurements. The very high temperatures in the core plasmas will broaden the lines to several electronvolts. Since some of the transitions have extremely short upper level lifetimes, natural line widths may be large and must be properly accounted for. The 3D resonance line in Ne-like W LXV, for instance, has a predicted radiative lifetime of around 350 as. This short decay time gives rise

[1]The radiative cooling rates for a given charge balance of Kr has been studied at the Berlin EBIT facility [12].

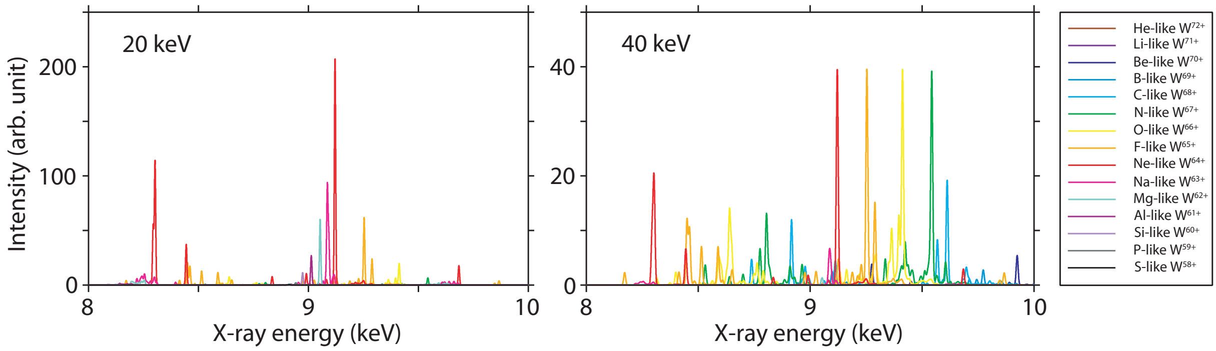

Figure 3: Theoretical spectra of W LIX – LXXIII at $N_e = 10^{14}$ cm^{-3} and $T_e = T_i$ = 20 and 40 keV.

to a line broadening of almost 1 eV[2]. Furthermore, the spectral neighborhood to the diagnostic lines must be studied as function of excitation energy since line blends from other charge states, including dielectronic recombination satellites [13], may alter the shapes of the observed spectral features. Figure 3 illustrates how the tungsten spectra in the 8 – 10 keV interval may look like for $T_e = T_i$ = 20 and 40 keV. The spectra have been modeled using FAC and include electron impact excitation, radiative and collisional cascades, dielectronic capture, and autoionization.

Acknowledgments

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[2]This may be compared to the ~1.5 fs lifetime and 0.2 eV natural line width of the Kr XXXV Kα w transition.